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DOI:

[10.1002/ett.2855](https://doi.org/10.1002/ett.2855)

*Document Version*

Peer reviewed version

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*Citation for published version (APA):*

Coll-Perales, B., Gozalvez, J., & Friderikos, V. (2016). Energy-efficient opportunistic forwarding in multi-hop cellular networks using device-to-device communications. *Transactions on Emerging Telecommunications Technologies*, 27(2), 249-265. <https://doi.org/10.1002/ett.2855>

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# Energy-efficient opportunistic forwarding in multi-hop cellular networks using device to device communications

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**Abstract** – Cellular networks face significant challenges as a result of the growth of cellular data traffic, with a significant portion of such traffic being delay tolerant. Multi-hop Cellular Networks (MCN) can help address the foreseen capacity and energy-efficiency constraints of cellular networks through the integration of cellular and Device to Device (D2D) communications. To this aim, this work proposes and studies the use of opportunistic store, carry and forward mechanisms in MCN networks to increase energy efficiency for delay tolerant traffic. In particular, the study first derives an analytical framework to identify in two hop scenarios the optimum mobile relay location and the location from which the mobile relay should start forwarding the information to the cellular base station in order to minimize the overall energy consumption. The derived optimum configuration is then used as a benchmark for the development of a context-based opportunistic MCN forwarding scheme that exploits context information provided by the cellular network. Numerical and simulation results demonstrate that significant energy benefits (above 90%) can be achieved through the use of opportunistic forwarding in MCN networks.

**Keywords** – Multi-hop cellular networks (MCN); mobile relay; opportunistic; store, carry and forward; energy efficiency; device to device (D2D).

## 1. Introduction

Cellular networks face significant capacity and energy challenges as a result of the continuous and exponential growth of cellular data traffic. Approaches to address these challenges include offloading traffic to Device to Device (D2D) communications [1] and Multi-hop Cellular Networks (MCN). MCNs substitute long-distance (and generally Non Line Of Sight, NLOS) direct links between the mobile user and the Base Station (BS) by various shorter links with improved link budgets. MCN networks initially focused on the use of fixed relays [2]. However, MCN networks that use mobile relays and D2D communications can offer significant capacity, Quality of Service (QoS) and energy benefits by opportunistically and collaboratively using the communications and computing resources of mobile devices [3]. These networks can also benefit from the integration of opportunistic networking. Opportunistic schemes exploit the node's mobility and the store, carry and forward paradigm to establish communication links between mobile relays based on contact opportunities. Traditional opportunistic multi-hop operation is characterized by intermittent ad-hoc connectivity between mobile relays that usually results in some end-to-end transmission delays [4].

However, it is important noting that delay tolerant services represent a significant portion of current mobile data traffic according to the latest Cisco's global mobile data traffic forecast [5]. Delay tolerant services include for example updates to social networking, emails, firmware and software updates, as well as certain cloud services. The delay tolerance of certain services can then be exploited by opportunistic schemes to search efficiency in the contact opportunities, and thereby reduce energy consumption without reducing the end-user Quality of Service (QoS). In this context, this paper studies the integration of opportunistic networking into MCN networks using mobile relays and D2D communications. In particular, the paper investigates the capacity of opportunistic schemes to reduce the energy consumption of delay tolerant services in 2-hop MCN uplink communications. To this aim, the paper first presents an analytical framework to identify the optimum mobile relay location, and the location at which the relay needs to start forwarding the information to the cellular network in order to minimize the overall energy consumption. This optimum configuration is then used as a benchmark for the design of an opportunistic forwarding scheme that relaxes the need to find a mobile relay located at

the identified optimum location and time instant. Instead, the source node waits for a mobile relay to reach the optimum location and then initiates the D2D transmission. This study proposes the use of context data to estimate the maximum time the source node should wait for a mobile relay to reach the identified optimum location. In particular, this study proposes using context data already available in cellular systems: density and distribution of mobile nodes within a cell. The study demonstrates that the proposed context-based opportunistic forwarding scheme for MCN networks using mobile relays and D2D communications can provide significant energy benefits for delay tolerant services compared to other forwarding schemes and traditional single-hop cellular communications.

The rest of this paper is organized as follows. Section 2 reviews related studies. Section 3 introduces the operation of opportunistic forwarding in MCN networks using mobile relays and D2D communications, and formulates the analytical framework for deriving optimum configurations. Section 4 describes the proposed context-based opportunistic forwarding scheme for MCN networks, and analyzes its energy performance bound. Section 5 compares the energy performance achieved by the proposed context-based opportunistic forwarding scheme to that obtained with other opportunistic forwarding schemes and single-hop cellular communications. Finally, Section 6 concludes the paper.

## 2. Related work

The capacity of MCN networks using mobile relays to reduce the energy consumption was first highlighted in [6]. This study divided cells into concentric rings, and showed that the overall energy consumption can be reduced if only mobile relays located at the innermost ring are allowed to directly transmit data to the cellular base station. On the other hand, users located in outer rings should find relays located at inner rings to reach the BS. The first experimental demonstration of such energy benefits was presented in [3] where the authors compare the energy consumed by single-hop uplink cellular transmissions to that consumed by a two-hop MCN connection using a mobile relay. The MCN connection achieved significant energy and QoS benefits by substituting the NLOS single-hop cellular link by two hops with improved link budget conditions and partial LOS conditions.

Opportunistic networking establishes multi-hop routes taking into account the presence of contact opportunities and the mobile nodes' inter-contact time. In the absence of forwarding opportunities,

mobile nodes store the message and wait for future occasions in which to forward the message to other nodes. This approach can increase the transmission delay, but it can also significantly reduce the energy consumption [7]. Opportunistic networking can also help offloading data traffic from cellular networks to metropolitan WiFi access points without degrading the QoS [8]. The integration of opportunistic networking into MCN networks can result in further benefits in terms of capacity, load balancing, co-channel interference and the possibility to switch-off low-utilization base stations [9]. To obtain such benefits, the authors formulate a finite space-time network graph that includes all possible routes for forwarding information towards a cellular BS. Such graph is constructed taking into account the delay tolerance acceptable for different services. The vertexes of the graph represent the location of the mobile relays with time, and the edges the transmission links. The authors claim that using the graph a BS can identify end-to-end opportunistic forwarding paths to achieve an established QoS goal. The study is further extended in [10] where the authors highlight the importance of considering the power consumption of storage units in mobile relays for the study of opportunistic networking.

## 3. Opportunistic forwarding in MCN networks

Studies published to date have demonstrated that significant benefits can be obtained from the use of opportunistic store, carry and forward mechanisms in cellular networks. However, opportunistic forwarding schemes can result in possible end-to-end transmission delays, and their use should be focused for delay tolerant services. Such services offer the possibility to manage the tolerable delay to design the integration of opportunistic networking into cellular systems towards a desired outcome. In the case of this study, the desired outcome is to reduce the total energy consumption.

This study considers a two-hop MCN scenario in which a static Source Node (SN) wants to transmit information to a Base Station (BS) using a Mobile Relay (MR) with store, carry and forward capabilities (Fig. 1). The study considers a delay tolerant service that requires the information to be transmitted to the BS within a time  $T$ . The time needed to transmit the information from SN to BS is computed taking into account: 1) the time needed for the D2D transmission from SN to MR (*D2D tx*), 2) the time that the MR stores and carries the information (*Store and carry*), and 3) the time needed by the MR to transmit the information to the BS (*Cellular tx*). As depicted in Fig. 1, estimating the time needed for each one of these processes requires determining the MR location

at which the D2D transmission should start ( $Opt\_X_i$ ), and the MR location at which the cellular transmission should start ( $Opt\_Y_i$ ). This section focuses then on estimating these two locations with the final objective to reduce the total energy consumption.

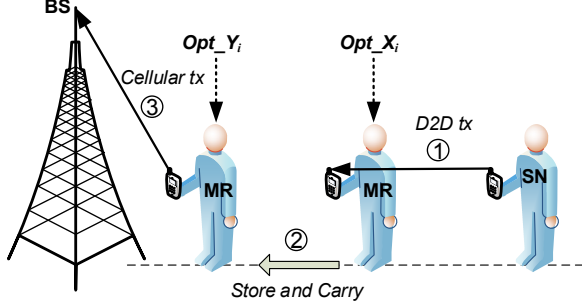


Fig. 1. 2-hop opportunistic MCN-MR scenario.

### 3.1. Problem formulation

A multi-objective constrained optimization problem is defined to identify the optimum MR location and the location at which the relay needs to start forwarding the information to the cellular network in order to minimize the overall energy consumption (eq. (1)-(4)). The objective function shown in eq. (1) has been defined together with two constraints (eq. (2) and (3)) and the requirement that the BS receives the information before a service-dependent deadline  $T$  (eq. (4)). This deadline  $T$  is discretized in the optimization framework as  $\{\tau_0, \tau_1 \dots \tau_{\Gamma}\}$ .

$$o.f : \min \left( \begin{array}{l} \sum_{\tau=\tau_0}^{\tau_{b-1}} (E_{D2D}(d_{SN-MR}, \tau) + \tau \cdot (P_R + P_W)) + \\ \text{--- (1) ---} \\ \sum_{\tau=\tau_b}^{\tau_{c-1}} \tau \cdot P_{IDLE} + \\ \text{--- (2) ---} \\ \sum_{\tau=\tau_c}^{\tau_{c+m}} (E_{cell}(d_{MR-BS}, \tau) + \tau \cdot P_W) \\ \text{--- (3) ---} \end{array} \right) \quad (1)$$

$$st : \sum_{\tau=\tau_0}^{\tau_{b-1}} TR_{D2D}(d_{SN-MR}) \cdot \tau \geq F \quad (2)$$

$$\sum_{\tau=\tau_c}^{\tau_{c+m}} TR_{cell}(d_{MR-BS}) \cdot \tau \geq F \quad (3)$$

$$0 \leq \tau_0 < \tau_{b-1} < \tau_b \leq \tau_{c-1} < \tau_c < \tau_{c+m} \leq T \quad (4)$$

The objective function (eq. (1)) is formulated considering the energy consumed by the *D2D tx* from SN to MR ①, the *Store and Carry* process ② and the *Cellular tx* ③ carried out by the MR. In ①,

$\sum_{\tau=\tau_0}^{\tau_{b-1}} E_{D2D}(d_{SN-MR}, \tau)$  is the energy consumed in the

D2D transmission between SN and MR within the time interval  $\{\tau_0, \tau_1 \dots \tau_{b-1}\}$ , and considering that SN and MR

are separated by  $d_{SN-MR}$  at  $\tau$ .  $\sum_{\tau=\tau_0}^{\tau_{b-1}} \tau \cdot (P_R + P_W)$  represents

the storage power consumption at the SN while transmitting the information, and the storage power consumption at the MR while receiving the information during the D2D transmission [10]. In ②,

$\sum_{\tau=\tau_b}^{\tau_{c-1}} \tau \cdot P_{IDLE}$  represents the power consumption at the

MR when the node stores and carries the information while moving towards the BS [10]. This process takes place within the time interval  $\{\tau_b, \tau_{b+1} \dots \tau_{c-1}\}$ . Finally,

$\sum_{\tau=\tau_c}^{\tau_{c+m}} E_{cell}(d_{MR-BS}, \tau)$  represents in ③ the energy

consumed in the cellular transmission from MR to BS within the time interval  $\{\tau_c, \tau_{c+1} \dots \tau_{c+m}\}$ , and considering that MR and BS are separated by  $d_{MR-BS}$  at

$\tau$ .  $\sum_{\tau=\tau_c}^{\tau_{c+m}} \tau \cdot P_W$  represents the storage energy consumption

at MR while transmitting the information to the BS during the time interval  $\{\tau_c, \tau_{c+1} \dots \tau_{c+m}\}$  [10].

The objective function is complemented with two constraints for the message (of size  $F$ ) to be completely transmitted in the D2D (eq. (2)) and cellular (eq. (3)) transmissions.  $TR_{D2D}$  and  $TR_{cell}$  represent the D2D (from SN to MR) and cellular transmission (from MR

to BS) rates respectively.  $\sum_{\tau=\tau_0}^{\tau_{b-1}} TR_{D2D}(d_{SN-MR}) \cdot \tau$  in eq.

(2) represents then the data transmitted in the D2D connection between SN and MR within the time interval  $\{\tau_0, \tau_1 \dots \tau_{b-1}\}$ , and considering that SN and MR

are separated by  $d_{SN-MR}$  at  $\tau$ .  $\sum_{\tau=\tau_c}^{\tau_{c+m}} TR_{cell}(d_{MR-BS}) \cdot \tau$  in eq.

(3) represents the data transmitted in the cellular communication from MR to BS within the time interval  $\{\tau_c, \tau_{c+1} \dots \tau_{c+m}\}$  considering that MR and BS are separated by  $d_{MR-BS}$  at  $\tau$ . The last constraint (eq. (4)) guarantees for the derived solution that the end-to-end transmission is completed before the service-dependent deadline  $T$ .

The defined optimization framework (eq. (1) to (4)) allows identifying the optimum 2-hop opportunistic MCN configuration that minimizes the overall energy consumption. For a given location of the SN, the optimization problem derives the time instances  $\tau_0, \tau_{b-1}$ ;  $\tau_b, \tau_{c-1}$ ; and  $\tau_c, \tau_{c+m}$  at which the *D2D tx*, *Store and Carry* and *Cellular tx* processes take place, respectively. This is in fact equivalent to identifying the optimum mobile relay location ( $Opt\_X_i$  in Fig. 1) and the location at which the relay needs to start forwarding the information to the cellular network

( $Opt\_Y_i$  in Fig. 1) in order to minimize the overall energy consumption. The optimization process (represented by  $\mathcal{G}$ ) can then be expressed as follows:

$$\begin{aligned} & [\tau_0, \tau_{b-1}, \tau_b, \tau_{c-1}, \tau_c, \tau_{c+m}, Opt\_X_i, Opt\_Y_i] = \\ & \arg \min (\mathcal{G}(F, T, TR_{D2D}, TR_{cell}, E_{D2D}, E_{cell}, P_R, P_W, P_{IDLE})) \end{aligned} \quad (5)$$

### 3.1.1. Transmission energy consumption

This study models the energy consumed in the transmissions between SN and MR, and between MR and BS, using the urban WINNER propagation model [11]. The study also considers that the signal power level at the receiver can be computed as:

$$P_R = G_T + G_R + P_T - PL \quad (6)$$

where  $G_T$  and  $G_R$  represent the transmitter and receiver antenna gain,  $P_T$  is the transmission power, and  $PL$  is the propagation loss. The transmission energy consumption is here computed considering that the transmission power ( $P_T$ ) is the necessary one to guarantee that the receiver's signal power level ( $P_R$ ) is equal to the threshold required for a successful communication between two nodes. It is then possible to estimate the transmission power under LOS conditions using the WINNER propagation model:

$$P_T^{LOS}(d) = \begin{cases} \frac{P_R \cdot 10^{4.1} \cdot (f/5)^2}{G_T \cdot G_R} d^{2.7} & \text{if } d < d_{bp} \\ \frac{P_R \cdot 10^{4.1} \cdot (f/5)^2}{G_T \cdot G_R \cdot d_{bp}^{1.73}} d^4 & \text{if } d \geq d_{bp} \end{cases} \quad (7)$$

where  $d$  is the separation distance between the transmitter and receiver (in meters),  $d_{bp} = 4(h_T - 1)(h_R - 1)/\lambda$  is the breakpoint distance ( $h_T$  and  $h_R$  are the transmitter and receiver antenna heights, and  $\lambda$  is the carrier wavelength, all of them in meters), and  $f$  is the carrier frequency in GHz.

The energy consumed in the D2D ( $E_{D2D}$ ) and MR to BS cellular ( $E_{cell}$ ) transmissions under LOS can then be expressed as:

$$E(d) = (e_r + e_t + e_{LOS}(d)) \cdot TR \quad (8)$$

where  $e_t$  and  $e_r$  represent the energy consumption per bit in the transmitter and receiver electronics respectively, and  $TR$  is the transmission rate ( $TR_{D2D}$  or  $TR_{cell}$ ).  $e_{LOS}$  represents the transmission energy consumption per bit under LOS conditions and is equal to  $P_T^{LOS}/TR$ . A similar process can be followed to estimate the NLOS transmission energy consumption.

### 3.1.2. Storage energy consumption

As recommended in [10], this study considers the energy consumed by storage units in mobile relays. Data packets received from wireless interfaces are automatically stored in the DRAM storage unit. The data packets could be transferred to internal units such as NAND flash to reduce energy consumption. This

decision usually depends on the time that the information is stored, and the transfer speed and power cost. If the information is transferred from DRAM to NAND, it must be transferred back to the DRAM when the mobile device decides to start any transmission process (*D2D tx* or *Cellular tx*). This work considers that the information is always transferred from DRAM to NAND flash (it is out of the scope of this paper to determine when it is worth transferring data from DRAM to NAND). As a result, the power state transitions of the two storage units needs to be considered when computing the storage energy consumption. These state transitions are depicted in Fig. 3 [10].  $P_R$  includes the power consumed by the DRAM and NAND flash when these storage units Read (*R*) and Write (*W*) the information, as well as the power consumed for transferring the information from DRAM to NAND flash at speed  $Transf\_DF$ .  $P_{IDLE}$  includes the power consumed by the NAND flash that is storing the information in *Idle* state, and the power consumed by the DRAM that is in *Idle\_self-refresh* state. Finally,  $P_W$  is the power consumed by the two storage units when they transfer the information back to the DRAM for transmission at speed  $Trans\_FD$ .

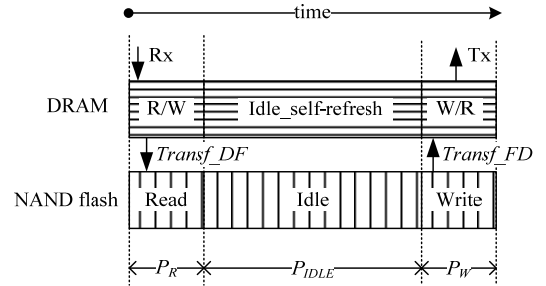


Fig.2. Transition states of the storage units as a function of the time when the data is transferred from DRAM to FLASH, and sent back to DRAM [10].

### 3.2. Evaluation scenario

The numerical resolution of the analytical framework described in the previous section is done considering the parameters summarized in Table 1. The evaluation considers LTE at 2GHz for the cellular transmissions, and IEEE 802.11g at 2.4GHz for the D2D transmissions<sup>1</sup>. These technologies have been selected based on the availability of the necessary models. In any case, the conclusions reported in this study are not dependent on the selected radio access technologies. Following the model reported in [12], the LTE transmission rate for the cellular link between MR and BS can be approximated as:

$$TR_{cell}(d) = r(N_{PRB}, I_{MCS}) \cdot (1 - p_{BLER}(N_{PRB}, I_{MCS})) \quad (9)$$

where  $r(N_{PRB}, I_{MCS})$  is defined in [12] as the maximum instantaneous data rate achievable by the user on

<sup>1</sup> 3GPP considers 802.11 technologies as well as cellular technologies (e.g. LTE-Direct) for device-to-device communications [1].

frequency chunk of size  $N_{PRB}$  Physical Resource Blocks (PRB) and modulation and coding scheme (MCS) index  $l_{MCS}$ .  $N_{PRB}$  has been set to 6 as in [13] and following the 3GPP guidelines in [14]. In addition,  $p_{BLER}(N_{PRB}, l_{MCS})$  is the Block Error Rate (BLER) experienced for an allocation size of  $N_{PRB}$  and MCS index  $l_{MCS}$ . As established in [12], this study considers a target BLER of 10% that coincides with that for the reported CQI values as described in the 3GPP physical layer procedures [15]. This study considers 15 MCS indexes (coinciding with the available CQI indexes in LTE) that are set according to the distance ( $d$ ) between the MR and the BS (more robust MCS are needed as the distance to the serving BS increases)<sup>2</sup>. MCS indexes for the allocated  $N_{PRB}$  are finally mapped to the Transport Block Size (TBS) indexes ( $l_{TBS}$ ) using the table reported in [15]. The  $r(N_{PRB}, l_{MCS})$  can then be calculated as:

$$r(N_{PRB}, l_{MCS}) = \frac{TBS}{T_{TBS}} \quad (10)$$

where  $T_{TBS}$  is the TBS duration which is equal to 0.5ms in LTE.

Using the model reported in [16], the IEEE 802.11g transmission rate for the D2D link between SN and MR can be expressed as follows:

$$TR_{D2D}(d) = \text{DataRate}(d) \cdot \text{Eff} \cdot (1 - \text{PER}(d)) \quad (11)$$

where  $\text{DataRate}$ ,  $\text{PER}$  and  $\text{Eff}$  represent the IEEE 802.11g transmission mode, Packet Error Ratio and channel efficiency, respectively.  $d$  is the distance between the transmitter and receiver (in meters). IEEE 802.11g defines twelve possible combinations of modulation and coding schemes that result in the set of data rates: {54, 48, 36, 24, 18, 12, 9, 6; 11, 5.5, 2, 1} Mbps. The data rate control algorithm dynamically selects the IEEE 802.11g data rate based on the link quality conditions. The IEEE 802.11g  $\text{DataRate}$  model used in this study has been empirically derived by the authors in [17]:

$$\text{DataRate}(d) = \begin{cases} 54 & d < 78.47m \\ \frac{54}{\frac{1}{78.47} - \frac{1}{270.85}} \cdot \left( \frac{1}{d} - \frac{1}{270.85} \right) & 78.47m \leq d < 270.85m \\ 0 & 270.85m \leq d \end{cases} \quad (12)$$

(12) indicates that the IEEE 802.11g  $\text{DataRate}$  is set to 54Mbps at short distances. More robust data rates are then used with increasing distances between SN and MR. The IEEE 802.11g  $\text{PER}$  model has also been empirically derived [17]:

$$\text{PER}(d) = \frac{0.75}{1 + e^{-0.019(d-115.15)}} \quad (13)$$

(13) indicates that the PER augments with the distance ( $d$ , in meters) between transmitter and receiver (despite using more robust modulation and coding schemes (12)), although an upper PER limit (0.75) is reached. The IEEE 802.11g channel efficiency ( $\text{Eff}$ ) represents the effective time that the 802.11g channel is used to transmit data, and depends on the transmission time of data packets ( $t_d$ ) and ACK packets ( $t_{ack}$ ), the contention period ( $t_{cont}$ ), and the inter-frame guard times ( $DIFS$  and  $SIFS$ ) [16]:

$$\text{Eff} = \frac{t_d}{DIFS + t_{cont} + t_d + SIFS + t_{ack}} \quad (14)$$

The energy consumption values for the DRAM and NAND flash storage units have been obtained from [18] and [19] respectively. The energy consumed per bit in the transmitter and receiver electronics ( $e_t$  and  $e_r$ ), and the power reception threshold ( $P_R$ ), have been obtained from [10]. The scenario considers the MR is in line with the SN, and moving towards the BS with a speed  $v$  of 2m/s. The SN needs to transmit to the BS a 10Mb ( $F$ ) file before a 100s deadline  $T$  [9].

Table 1. Evaluation parameters

Parameter	Description	Value
$R$	Cell radius	1000m
$v$	Mobile nodes' speed	2m/s
$F$	File size	10Mb
$T$	Transmission deadline	100s
$G_T, G_R$	Transmitter and receiver antenna gain	1
$e_t, e_r$	Energy consumed per bit by the transmitter/receiver	$50 \times 10^{-9}$ J/b
$P_R$	Power reception threshold	-52dBm
$h_{SN}, h_{MR}, h_{BS}$	Antenna height of SN, MR and BS	1.5m, 1.5m, 10m
$DRAM P_R, P_W, P_{Idle\_self-refresh}$	DRAM power consumed for Reading, Writing and in Idle_self-refresh state	252mW, 252mW, 1.35mW
$NAND \text{ } Eff_{Read}, Eff_{Write}, P_{Idle}$	NAND efficiency for Reading and Writing, and Power consumed in Idle state	1.83nJ/b, 11.92nJ/b, 0.4mW
$Transf\_DF, Transf\_EF$	Transfer speed from the DRAM to the NAND flash and vice versa	4.85 MiB/s, 927.1 KiB/s

### 3.3. Optimum configuration of opportunistic forwarding in MCN networks

The optimization problem presented in Section 3.1 has been solved for all possible distances between SN and BS. Fig. 3-left shows the optimum MR location at which to start the D2D transmission as a function of the distance between SN and BS (labeled 'Optimum'). The MR location is represented by means of the distance between SN and MR. For example, if SN is located 400m away from the BS, the MR should be ideally located 50m away from the SN in the direction of the BS in order to minimize the total energy consumption. Fig. 3-left shows that the distance

<sup>2</sup> The cell is divided into 15 equally spaced and concentric rings identified by the MCS indexes.

between SN and the optimum MR that minimizes the energy consumption increases with the distance between SN and BS. This is to reduce the distance at which the MR starts forwarding the information towards the BS (and therefore the cellular transmission energy consumption). However, the *D2D tx* energy consumption increases as the MR is selected closer to the BS. As a result, the distance between SN and the optimum MR location only increases when the energy saving of the Store and Carry process (that allows reducing the cellular transmission distance from MR to BS) can compensate the increase in the *D2D tx* energy consumption. Fig. 3-left shows a small augment in the MR location when the SN is located very close to the BS. This is because the optimum MR does not store and carry the information when the SN is close to the BS (further details are provided below), and therefore the SN selects a MR as close as possible to the BS. The energy consumption levels for the *D2D tx* from SN to the optimum MR location are reported in Fig. 3-right in logarithmic scale as a function of the distance between SN and BS. The increasing distances between SN and the optimum MR location (Fig. 3-left) result in that the *D2D tx* energy consumption levels increase with the distance between SN and BS.

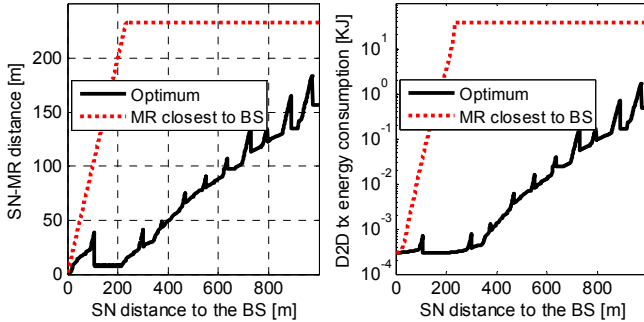


Fig. 3. *D2D tx*: optimum MR location (left) and *D2D tx* energy consumption (right).

To demonstrate how important is to adequately select the MR, Fig.3 also shows the results obtained with a scheme in which the SN selects the MR that provides the higher progress towards the BS [20]. This scheme is referred to as ‘MR closest to BS’ in this paper. For a fair comparison, a similar optimization process to that reported in Section 3.1 is conducted for this scheme. The optimization process derives for this scheme the MR location that provides the highest progress towards the BS and the location at which the MR should start forwarding the information to the BS. In this case, if the SN is located 400m away from the BS, the MR should be located 230m away from the SN in the direction towards the BS (Fig. 3-left). The higher *D2D tx* transmission distances of the ‘MR closest to BS’ scheme with respect to the ‘Optimum’ proposal (Fig.

3-left) result in the significant increase in the *D2D tx* energy consumption depicted in Fig. 3-right.

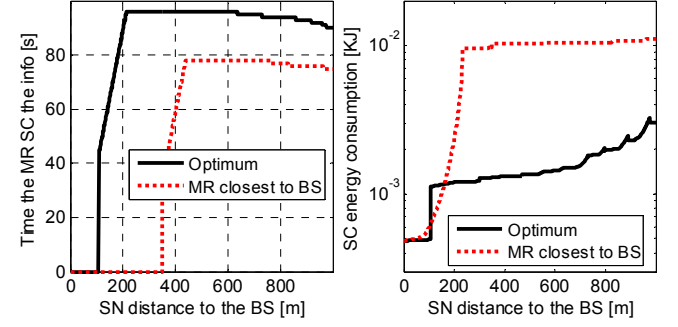


Fig. 4. Store and Carry (SC): time the MR stores and carries the information while moving towards the BS (left) and SC energy consumption (right).

Once the *D2D tx* from SN to the optimum MR is completed, the MR needs to store and carry the information towards the BS from the location identified in Fig. 3-left. Fig. 4-left shows the time that the optimum MR stores and carries (SC) the information in order to minimize the total energy consumption (‘Optimum’ in Fig. 4). Fig. 4-left shows that if an SN is located 400m away from the BS, the optimum MR needs to store and carry the information for 96s before transmitting it to the BS using cellular communications. The obtained results indicate that when the SN is close to the BS, the optimum MR does not need to store and carry the information. The MR should instead forward it to the BS as soon as received from the SN. This is because the energy consumption of the store and carry process does not compensate the energy savings resulting from forwarding the information at distances closer to the BS. Despite the fact that the optimum MR does not store and carry the information, the results depicted in Fig. 4-right shows non null SC energy consumption levels when SN is close to the BS. This is because the SC energy consumption also includes the storage energy consumption at SN and MR while transmitting and receiving the information ( $P_R$  and  $P_W$ ). As the distance from SN to the BS increases, the optimum MR needs to store and carry the information so that its cellular transmission starts closer to the BS where higher cellular data rates are possible. However, for high distances between SN and BS, the time the MR stores and carries the information to minimize the total energy consumption slightly decreases. The results depicted in Fig.4-right also show that the SC energy consumption levels increase with the distance between SN and BS. These two effects are due to the increase in the time needed to complete the *D2D tx* (Fig. 3-left) and cellular transmissions (Fig. 5-left). Fig. 5-left shows the time the optimum MR needs to transmit the information to the BS using its cellular radio interface,



while Fig. 5-right reports the resulting cellular transmission energy consumption levels.

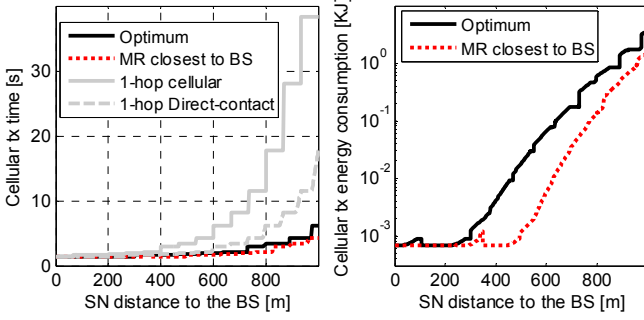


Fig. 5. Cellular tx: time the MR requires to transmit the data to the BS (left) and energy consumption (right).

The impact of selecting the MR that provides the highest progress towards the BS ('MR closest to BS' in Fig. 4) on the *Store and Carry* process is twofold. First, the time the MR stores and carries the information (Fig.4-left) is reduced compared with the optimum configuration ('Optimum'). For example, if SN is located 400m away from the BS, the time the MR stores and carries the information is reduced to 59s. Second, the SC energy consumption levels (Fig.4-right) increase compared to the optimum configuration despite reducing the time the MR stores and carries the information (Fig. 4-left). These two trends are observed because of the higher time necessary for finishing the *D2D tx* from SN to MR when MR is selected as close as possible to the BS. This reduces the time needed to upload the information to the BS (Fig. 5-left), and therefore the cellular transmission energy consumption (Fig. 5-right). However, it also results in shorter times available for the MR to store and carry the information, and therefore increases the energy consumption at SN and MR while transmitting and receiving the information ( $P_R$  and  $P_W$ ), respectively.

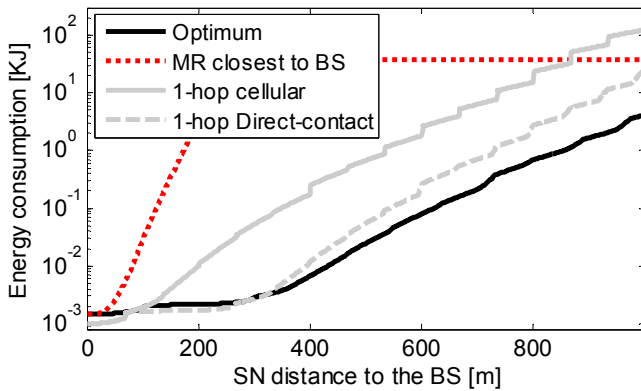


Fig. 6. Total energy consumption.

Using the configurations illustrated in Figures 3, 4 and 5, the optimum MR location ('Optimum') results in significant total energy savings for the end-to-end

transmission of the file before  $T$  from SN to BS (Fig. 6). On average, the total energy consumption can be reduced by 92% when using the derived optimum configuration for opportunistic MCN communications with respect to the 'MR closest to BS' approach. The lower cellular transmission energy consumption levels (Fig. 5-right) obtained when selecting the MR as close as possible to the BS cannot compensate the higher D2D transmission (Fig. 3-right) and SC (Fig. 4-right) energy consumption levels. The obtained results clearly demonstrate the need to adequately configure opportunistic MCN communications to achieve the desired objectives in terms of energy efficiency.

For comparative purposes, the energy consumption of single-hop cellular communications has also been evaluated and is reported in Fig. 6. The '1-hop cellular' configuration refers to the case in which the static SN transmits the file directly to the BS. In the '1-hop Direct-contact' configuration, the SN is mobile, and can store, carry and forward the information to the BS without using a mobile relay; this scheme is usually referred to as Direct-contact in the literature [21]. For a fair comparison, the '1-hop Direct-contact' configuration follows a similar optimization process to that reported in Section 3.1 to derive the optimum location at which the moving SN should start forwarding the information to the BS in order to minimize the total energy consumption. The obtained results show that when SN is very close to BS, there are no energy benefits from using opportunistic MCN communications compared to single-hop cellular schemes. However, as the distance increases, an optimum configuration of opportunistic MCN communications can significantly reduce the total energy consumption compared to single-hop cellular schemes; please note that energy consumption levels in Fig.6 are shown in logarithmic scale. For example, when SN is 200m away from the BS, the optimum configuration ('Optimum') reduces the total energy consumption by approximately 75% compared to traditional single hop cellular communications ('1-hop cellular'). The reduction augments to approximately 98% at the cell edge. The Direct-contact scheme ('1-hop Direct-contact') reduces the total energy consumption compared to traditional single-hop cellular communications (on average by 85%), but cannot achieve the total energy consumption levels than an optimum configuration of opportunistic MCN communications can reach. In fact, such optimum configuration can reduce the total energy consumption by up to 85% (on average by 77%) compared to the Direct-contact scheme.



#### 4. Context-based opportunistic forwarding

The previous study has identified optimum configurations for 2-hop opportunistic MCN communications. In particular, the study has identified the optimum MR location and the location at which the MR should start forwarding the information to the BS in order to minimize the overall energy consumption. The optimum configuration can help establish an energy-efficiency performance bound. However, it is hardly likely that in a real scenario a MR can be found at the identified optimum location and time instant. Suboptimum solutions are therefore needed to select an MR. This section presents an alternative context-based opportunistic forwarding scheme that uses the optimum MR location identified in Section 3, but delays the start of the *D2D tx* until a MR is found at the identified optimum location. This approach improves the feasibility of the proposed context-based opportunistic forwarding scheme compared to the optimum configuration since it does not require a MR to be located exactly at the identified optimum location and time instant.

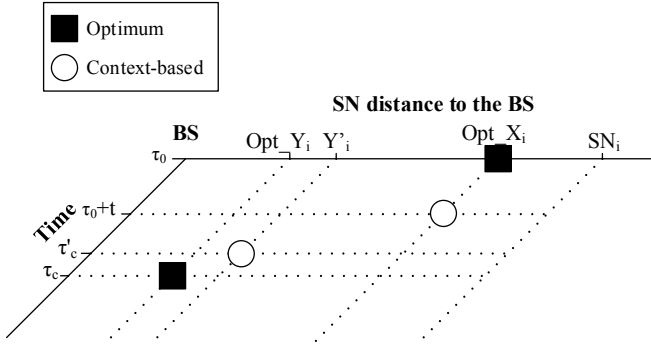


Fig. 7. Optimum and suboptimum ('Context-based') configurations of 2-hop opportunistic MCN communications.

The space-time graph shown in Fig. 7 is used to represent and compare the 2-hop opportunistic MCN operation for the optimum configuration identified in Section 3 ('Optimum'), and the new suboptimum approach that delays the *D2D tx* until a MR reaches the identified optimum location ('Context-based'). For the optimum configuration, the *D2D tx* between  $SN_i$  and the optimum MR located at  $Opt\_X_i$  starts at time instant  $\tau_0$ . The MR stores and carries the information from  $Opt\_X_i$  until it reaches the  $Opt\_Y_i$  location at time instant  $\tau_c$ , and initiates the *Cellular tx*. The suboptimum configuration considers the scenario which  $SN_i$  cannot find a MR at the optimum location ( $Opt\_X_i$ ) and time instant  $\tau_0$ . In this case, the proposed suboptimum scheme delays the *D2D tx* until a MR arrives at  $Opt\_X_i$ . We denote as  $t$  the time  $SN_i$  should delay the *D2D tx* to guarantee a MR reaches the identified optimum location (additional details are presented below). When such node reaches the optimum location,  $SN_i$  can start the *D2D tx*. After store

and carrying the information, MR would start the *Cellular tx* to the BS. However, since the transmission has to end before the deadline  $T$ , and the suboptimum scheme has delayed the start of the *D2D transmission*, the start of the forwarding process to the cellular BS cannot start at the  $Opt\_Y_i$  location and time  $\tau_c$  but instead at location  $Y'_i$  and time  $\tau'_c$ .

##### 4.1. Definition

The suboptimum scheme requires SN to delay the *D2D tx* for  $t$  seconds until a MR reaches the optimum MR location identified in Section 3. The definition of this time  $t$  is subject to the fulfillment of the following two conditions. First, it is necessary to guarantee with certain probability that at least one MR reaches the identified optimum MR location before  $t$  seconds elapse. This paper proposes to identify and establish the probabilistic requirement using context information that can be extracted from cellular networks (statistical information about the spatial density and distribution of mobile nodes within a cell). The second condition is that the BS must still receive the complete file before the service-dependent deadline  $T$ , even if SN had to delay the *D2D tx* waiting until an MR reached the optimum MR location. This condition must be satisfied independently of whether SN has to exhaust or not the delay time  $t$  to find an MR at the identified optimum location. If these two conditions are not fulfilled, a satisfactory opportunistic MCN transmission is considered unfeasible, and SN should directly transmit the information to the cellular BS through a traditional single-hop cellular link.

###### a) Uniform distribution of nodes within the cell

Based on the previous definition,  $t$  represents the time the SNR needs to delay the start of the *D2D tx* in order to guarantee with certain probability the arrival of at least one MR at the identified optimum MR location. To determine its value, this study first considers that mobile devices are uniformly distributed within the cell. Using the Poisson distribution, the probability that a MR reaches the identified optimum MR location can be calculated as follows [22]:

$$P_{Opt\_X_i} = P(x > 0; \mu' t) = 1 - P(x = 0; \mu' t) = 1 - \frac{(\mu' t)^0 \cdot \exp(-\mu' t)}{0!} = 1 - \exp(-\mu' t), \quad \forall Opt\_X_i \in (1, \dots, R) \quad (15)$$

where  $\mu'$  represents the average arrival rate of MRs to the identified optimum MR location (actually to any location within the cell) and  $t$  corresponds to the inter-arrival delay time (or the time to the next arrival of a MR to the identified location).  $\mu'$  is computed using the average number of MRs ( $\mu$ ) uniformly distributed within a cell of radius  $R$  and the nodes' speed  $v$ :

$$\mu' = \frac{\mu \cdot v}{R} \quad (16)$$

The time  $t$  that guarantees with probability  $\delta$  the arrival of a MR at the identified optimum MR location  $Opt\_X_i$  can be expressed as shown in (18):

$$P_{Opt\_X_i} = 1 - \exp(-\mu \cdot t) = \delta \quad (17)$$

$$t = \frac{R \cdot \ln(1 - \delta)}{-\mu \cdot v} \text{ iff } \exists Y'_i = \underset{\tau'_{b-1} = \tau_{b-1} + t}{\operatorname{argmin}} (\mathcal{G}(\dots)) \quad (18)$$

As shown in (18), the  $D2D$  tx delay  $t$  that guarantees the arrival of at least one MR at the identified optimum MR location is proportional to the cell radius ( $R$ ) and inversely proportional to the average spatial density of nodes within the cell ( $\mu/R$ ) and to the nodes' speed ( $v$ ). In addition,  $t$  increases with the probability  $\delta$  guaranteeing the presence of the MR at the identified optimum MR location. It is important noting that the derived delay time  $t$  represents the worst case, i.e. the maximum time the SN should delay the  $D2D$  tx waiting for a MR to reach the optimum MR location. In this context, the delay time  $t$  can be defined if and only if (iff) the condition shown in (18) is also fulfilled. The condition requires that there exists a suboptimum solution  $Y'_i$  of the optimization problem ( $\mathcal{G}$ ) presented in Section 3.1, considering that the  $D2D$  tx would finish at time instant  $\tau_{b-1} + t$  (the optimum configuration needs  $\tau_{b-1}$  to carry out the  $D2D$  tx from SN to MR). If this condition is met, it is possible to establish the communication with the BS through a 2-hop opportunistic MCN link. If the condition is not met, the SN will transmit the information directly to the BS through a traditional single-hop cellular link.

*b) Non-uniform distribution of nodes within the cell*  
The delay time  $t$  can also be computed when the distribution of users within the cell is non-uniform. Without loss of generality, this study considers a distribution in which the spatial density of nodes is higher close to the BS. This is actually a common assumption in the literature since it represents scenarios where BSs are deployed to provide coverage to frequently visited places. Following [23], the mathematical model of this non-uniform distribution has been represented by means of a truncated Normal distribution centered at the BS. The truncated Normal distribution can be expressed as follows [22]:

$$P(x; s, \sigma, a, b) = \begin{cases} \frac{\phi\left(\frac{x-s}{\sigma}\right)}{\sigma \cdot Z}, & \text{if } x \in [a, b] \\ 0, & \text{if } x \notin [a, b] \end{cases} \quad (19)$$

where  $\phi(\xi)$  represents the probability density function of the standard Normal distribution. The Normal distribution of a random variable  $x$  with mean  $s$  and variance  $\sigma^2$  can be expressed as [22]:

$$P(x; s, \sigma) = \frac{1}{\sqrt{2 \cdot \pi} \sigma} \exp\left(-\frac{(x-s)^2}{2\sigma^2}\right), \quad -\infty \leq x < \infty \quad (20)$$

In (19),  $Z$  is the Cumulative Distribution Function (CDF) difference at the upper ( $b \setminus x \in [-\infty, b]$ ) and lower ( $a \setminus x \in [a, \infty]$ ) bounds:

$$Z = \Phi\left(\frac{b-s}{\sigma}\right) - \Phi\left(\frac{a-s}{\sigma}\right) \quad (21)$$

being the CDF defined as:

$$\Phi(x) = F(x) = P(X \leq x) = \int_{-\infty}^x P(x; s, \sigma) dx \quad (22)$$

The probability to find one MR at the identified optimum MR location  $Opt\_X_i$  can be calculated using (19):

$$P_{Opt\_X_i} = \int_{Opt\_X_i - \varepsilon/2}^{Opt\_X_i + \varepsilon/2} P(x; s, \sigma, a, b) dx \quad (23)$$

where  $\varepsilon$  represents the spatial discretization unit. Considering that the average spatial density of nodes in the cell is equal to  $\mu/R$ , the average spatial density of nodes at  $Opt\_X_i$  can then be computed as  $\mu_{Opt\_X_i} = (\mu/R) \cdot P_{Opt\_X_i}$ . Following the indications in [24], the truncated Normal distribution can be discretized into many Poisson distributions. This allows carrying out a similar analysis to that presented in (15)-(18) for the uniform distribution of nodes within the cell, and thereby calculate the time  $t$  the SN needs to delay the  $D2D$  tx to guarantee with probability  $\delta$  the arrival of a MR at the identified optimum location under non-uniform distribution of nodes within the cell.  $t$  can be calculated as follows:

$$t = \frac{R \cdot \ln(1 - \delta)}{-\mu \cdot P_{Opt\_X_i} \cdot v} \text{ iff } \exists Y'_i = \underset{\tau'_{b-1} = \tau_{b-1} + t}{\operatorname{argmin}} (\mathcal{G}(\dots)) \quad (24)$$

It is important noting that (24) depends on  $P_{Opt\_X_i}$  and thus on the optimum MR location ( $Opt\_X_i$ ) within the cell (it was not the case when nodes are uniformly distributed within the cell). The definition of (24) is also subject to the fulfillment of the condition that there exists a suboptimum solution of the optimization problem ( $\mathcal{G}$ ) presented in Section 3.1. If this condition is not met, the SN transmits the file to the BS using a traditional single-hop cellular link.

#### 4.2. Worst-case conditions

This section evaluates the worst-case performance of the proposed context-based opportunistic forwarding scheme considering the scenario characterized by the parameters summarized in Table 1. The worst-case scenario in case of opportunistic transmissions is experienced when SN needs to delay the  $D2D$  tx for the full time  $t$ . In a real operation, it might happen that SN does not need always to delay the  $D2D$  tx by  $t$  seconds if a MR arrives earlier to the optimum MR

location; this scenario will be evaluated in Section 5. The previous section showed that the  $D2D$  tx delay time  $t$  that guarantees with probability  $\delta$  (set to 0.8 in this section) the arrival of a MR at the identified optimum location depends on the spatial density and distribution of nodes within the cell. The study here presented considers uniform and non-uniform distributions of nodes and different spatial densities of nodes ( $\mu/R=\{0.1, 0.05\}$  MRs/m) within the cell. In the case of a non-uniform distribution of nodes within the cell, this section considers a standard deviation  $\sigma$  equal to 300m (this means that approximately 68% of the nodes are located at distances closer to 300m to the BS with cell radius equal to 1000m).

Fig. 8 shows the time  $t$  the SN needs to delay the  $D2D$  tx waiting for a MR to arrive at the identified optimum MR location in the worst-case scenario.  $t$  is depicted as a function of the distance between SN and BS, and is computed following (18) and (24) for uniform and non-uniform distributions of nodes within the cell, respectively. The optimum MR location was reported in Fig. 3-left as a function of the distance between SN and BS. Fig. 8.a shows, for example, that when nodes are uniformly distributed within the cell, a SN located 400m away from the BS needs to delay the  $D2D$  tx by 16.1s waiting for a MR to arrive at the optimum MR location (the optimum MR location was at a 50m distance away from the SN in the direction of the BS according to Fig. 3-left).

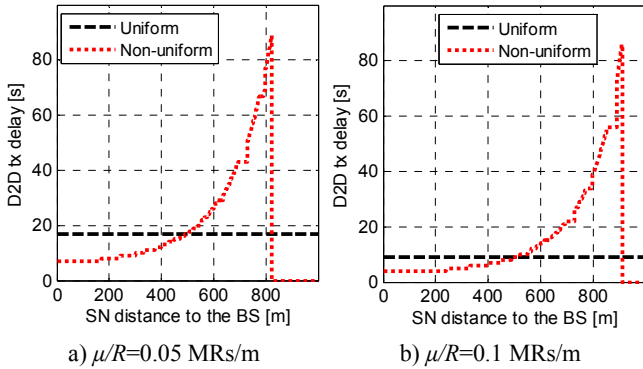


Fig. 8.  $D2D$  tx delay time  $t$  to guarantee the arrival of at least one MR at the identified optimum MR location with  $\delta$  equal to 0.8.

The results reported in Fig. 8 show that under uniform distribution of nodes  $t$  is constant for any location of the SN within the cell, but decreases as the spatial density of nodes within the cell increases (from to 16.1s to 8.05s when the spatial density of MRs increases from 0.05 MRs/m – Fig. 8.a – to 0.1 MRs/m – Fig. 8.b). Fig. 8 also shows that under non-uniform distribution of nodes within the cell,  $t$  increases with the distance between SN and BS in order to compensate the smaller density of users as we increase the distance to the BS. The considered non-uniform distribution scenario results in very low densities of

nodes at the cell edge. At the cell edge, the  $D2D$  tx delay  $t$  that would guarantee the arrival of an MR at the optimum location is therefore too high for opportunistic MCN transmissions to be completed before the service-dependent deadline  $T$ . In this case, SNs close to the cell edge (e.g. at distances higher than 912m when  $\mu/R=0.1$  MRs/m, Fig. 8.b) should directly transmit the information to the cellular BS, which is represented by a  $t$  value equal to 0 in Fig. 8.

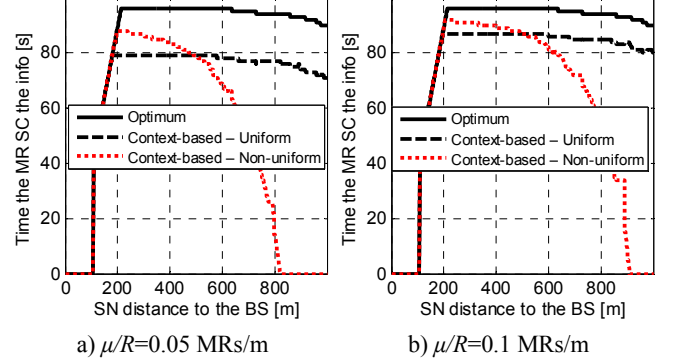


Fig. 9. Time the MR stores and carries the info towards the BS.

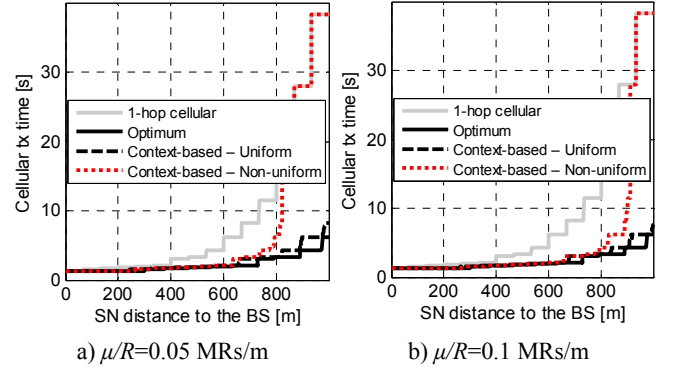


Fig. 10. Time the MR requires to transmit the data to the BS.

As a consequence of delaying the start of the  $D2D$  tx at the SN, the selected MR at the identified optimum location needs to adjust its opportunistic operation compared with the optimum configuration derived in Section 3.1. Fig. 9 shows for the context-based opportunistic forwarding proposal the time the MR would store and carry the information from the optimum MR location until it starts its cellular transmission to the BS in order to minimize the total energy consumption. The reported time is shown in Fig. 9 for the uniform ('Context-based – Uniform') and non-uniform distribution ('Context-based – Non-uniform') of users within the cell. When compared with the optimum configuration ('Optimum' in Fig. 9), the context-based opportunistic forwarding scheme reduces the time the MR is allowed to store and carry the information towards the BS as a result of the need to delay the  $D2D$  tx at the SN. For example, when SN is located 400m away from the BS, the selected MR stored and carried the information for 96s in the optimum configuration. When considering the context-

based proposal for real deployments, this time is reduced to 79s (Fig. 9.a, uniform distribution of nodes within the cell and  $\mu/R=0.05$  MRs/m). The results depicted in Fig. 9 also show that under non-uniform distribution of nodes within the cell, the time the MR stores and carries the information considerably reduces with the increasing distance between SN and BS. This is the case because of the increasing delay in the  $D2D$  tx with the distance between SN and BS (Fig. 8).

The time the selected MR stores and carries the information reduces the cellular communications distance with the BS (which allows using higher cellular data rates). The reduction in the time the selected MR located can store and carry the information with the proposed context-based scheme (Fig. 9) results in higher durations of the cellular transmission to the BS when compared with the optimum configuration (Fig. 10). However, the context-based proposal reduces the time of the cellular transmission compared with traditional single-hop cellular communications from SN to BS ('1-hop cellular' in Fig. 10). In addition, it is important remembering that the context-based proposal provides a solution to an unfeasible optimum configuration of opportunistic MCN communications in the case no MR can be found at the identified optimum location and requested time instant.

The changes in the time the MR stores and carries the information (Fig. 9) and the time it needs to transmit the information to the BS (Fig. 10) result in the differences observed in terms of total energy consumption between the context-based proposal and an optimum configuration of 2-hop opportunistic MCN communications (Fig. 11). However, it is important highlighting that in worst-case scenarios, the context-based proposal only results in minor degradations of the energy performance compared to the optimum configuration. In fact, while the optimum configuration reduces the average energy consumption compared to single-hop cellular transmissions (from SN to BS) by 97%, the context-based scheme achieves reduction levels of 95% (spatial density equal to 0.1 MRs/m and uniform distribution of nodes) and 94% (spatial density equal to 0.05 MRs/m and uniform distribution of nodes). Under non-uniform distribution of nodes within the cell, the reduction is equal to 61% and 51% when using the context-based forwarding proposal and the spatial density of nodes is equal to 0.1 MRs/m and 0.05 MRs/m respectively. These results clearly highlight that opportunistic MCN communications still provide clear energy benefits compared to single-hop cellular communications under real deployments where

ideal or optimum conditions cannot be met<sup>3</sup>. In addition, it is important remembering that the results shown in Fig. 11 correspond to worst-case conditions for the proposed context-based scheme (SN needs to wait for  $t$  seconds before finding an MR in the identified optimum location).

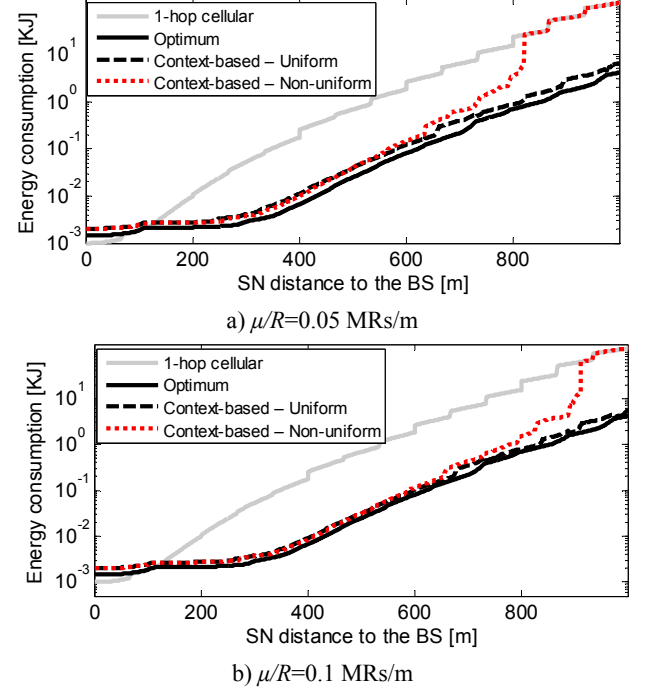


Fig. 11. Total energy consumption.

## 5. Performance evaluation

The previous section has numerically evaluated the energy performance of the proposed context-based opportunistic forwarding scheme under worst case conditions. Such worst-case conditions correspond to the case in which the SN had to delay by  $t$  seconds the  $D2D$  tx to find a MR at the optimum location with certain probability. However, it is possible that the SN finds a MR at the optimum location before the  $t$  seconds expire. If this is the case, the context-based scheme starts the  $D2D$  tx as soon as a MR arrives at the optimum location, and does not wait until  $t$  expires. On the other hand, if  $t$  expires before any potential MR reaches the optimum location, the context-based scheme requests the SN to directly transmit the information to the BS using single-hop cellular communications. To evaluate the energy performance under these dynamic conditions, it is necessary to simulate a scenario with mobile nodes moving towards the BS under uniform and non-uniform distributions. The parameters selected for the simulated scenario are those already summarized in Table 1.

<sup>3</sup> Following the previous discussions, the benefits are reduced at the cell edge for non-uniform distribution of users within the cell. The reduction is influenced by the spatial density of users within the cell.

Table II. Reduction (in percentage) of the total average energy consumption compared to single-hop cellular communications.

a) Uniform Spatial Distribution of MRs

Technique	$\mu/R=0.1$ MRs/m		$\mu/R=0.05$ MRs/m	
	$\delta=0.9$	$\delta=0.8$	$\delta=0.9$	$\delta=0.8$
Context-based – Cell	94.45	86.88	92.88	85.91
Context-based – Ring	96.37	94.51	95.23	92.52
MR closest to BS	18.74		23.91	
MR closest to SN	86.24		86.25	
Full knowledge	96.86		96.77	
1-hop Direct-contact	86.72			
Optimum	97.01			

b) Non-uniform Spatial Distribution of MRs

Technique	$\mu/R=0.1$ MRs/m		$\mu/R=0.05$ MRs/m	
	$\delta=0.9$	$\delta=0.8$	$\delta=0.9$	$\delta=0.8$
Context-based – Cell	55.43	48.12	41.98	37.51
Context-based – Ring	94.99	92.24	93.00	89.92
MR closest to BS	24.14		33.24	
MR closest to SN	86.39		89.87	
Full knowledge	96.72		95.90	
1-hop Direct-contact	86.72			
Optimum	97.01			

The performance of the proposed context-based opportunistic forwarding scheme is here compared against that obtained with 5 other reference schemes: traditional single-hop communications ('1-hop cellular'); Direct-contact single-hop cellular communications (Section 3.3, '1-hop Direct-contact'); 2-hop MCN communications with the SN selecting the MR that provides the higher progress towards the BS ('MR closest to BS'); the optimum configuration of 2-hop opportunistic MCN communications ('Optimum')<sup>4</sup>; 2-hop opportunistic MCN communications in which SN selects the MR that is closer to itself [25] ('MR closest to SN')<sup>5</sup>; and a final 2-hop opportunistic MCN scheme proposed in [9] and that is here referred to as 'Full knowledge'. This scheme assumes that a BS can collect all the information about the location and mobility of mobile nodes in the cell, and use this information to identify the MR that minimizes the total energy consumption. Two variants of the proposed context-based opportunistic forwarding scheme are evaluated in this section depending on how the cellular network provides the context information (spatial density of users) needed to calculate  $t$ . When such information is provided per cell, the proposed context-based scheme is referred to as 'Context-based – Cell'. If the information is provided for the concentric rings that define a cell, the scheme is referred to as 'Context-based – Ring'. In this study, we consider that the cell is

divided into 15 rings; a LTE transmission mode is assigned to each ring (Section 3)<sup>6</sup>. The evaluation of the different schemes is conducted for all possible distances between SN and BS.

Table II shows the reduction in the total average energy consumption achieved by the different evaluated schemes compared to the traditional single-hop cellular communications. The depicted results clearly show that the use of opportunistic forwarding schemes helps reducing the energy consumption. In the case of 2-hop opportunistic MCN communications, the energy gains depend on how the MR is selected. Selecting the MR that provides the higher progress towards the BS is shown to significantly reduce the energy benefits compared to the other schemes as a result of the high energy being consumed in the D2D transmission (Section 3, Fig. 3). The higher energy performance is achieved with the optimum configuration and the 'Full knowledge' scheme. As already explained, the optimum configuration assumes there is always an MR at the identified optimum location at the time of starting a D2D transmission which is unrealistic. For example, the probability that SN finds an MR at the optimum location at the start of the D2D transmission is 0.12 with a uniform spatial density of 0.05MRs/m and 0.23 with a uniform spatial density of 0.1MRs/m. The implementation of the 'Full knowledge' reference scheme requires all nodes to continuously inform the BS of their exact location and mobility information. Collecting this information at the BS would generate a very significant signaling overhead. In fact, the conducted simulations show that the 'Full knowledge' reference scheme increases on average the signaling overhead by 50% if compared with the proposed context-based opportunistic forwarding scheme. The results in Table II show that the proposed context-based opportunistic forwarding scheme for 2-hop MCN communications achieves an energy performance close to that obtained with the optimum configuration and the 'Full knowledge' reference scheme. The differences reduce with the increasing density of mobile nodes within the cell. This is the case because the time the context-based proposal needs to delay the D2D tx from SN to an MR in the optimal location decreases with increasing density of nodes. As a result, the selected MR will have more time to store and carry the information, and it will start the cellular transmission closer to the BS. Reducing the probability  $\delta$  also decreases the time by which the

<sup>4</sup> The performance of the optimum configuration is taken from the numerical analysis reported in Section 4 that assumes that it is always possible to find an MR at the identified optimum location and desired time instant.

<sup>5</sup> A similar optimization process to that reported in Section 3 is conducted for determining the location at which the selected MR should forward the information towards the BS.

<sup>6</sup> Both variants of the context-based proposal estimate  $t$  using the expression derived for a uniform distribution of nodes within the cell (eq. 18). In the case the context information is provided per ring, the spatial density of users in (18), i.e.  $\mu/R$ , should be replaced by  $\phi/r$  with  $\phi$  representing the average number of nodes in the ring where the optimum MR location is located, and  $r$  the ring length.

context-based proposal needs to delay the start of its *D2D tx*. However, in this case, the energy performance of the context-based proposal decreases with the probability  $\delta$ . This is due to the fact that as this probability decreases, a lower percentage of 2-hop opportunistic MCN connections are established between SN and BS (Table III).

Table III. Hit Rate: percentage of SN-BS links established using 2-hop opportunistic MCN communications.

a) Uniform Spatial Distribution of MRs				
Technique	$\mu/R=0.1$ MRs/m		$\mu/R=0.05$ MRs/m	
	$\delta=0.9$	$\delta=0.8$	$\delta=0.9$	$\delta=0.8$
Context-based – Cell	93.4	86.2	98.7	83.4
Context-based – Ring	98.6	91.5	99.8	86.8

b) Non-uniform Spatial Distribution of MRs				
Technique	$\mu/R=0.1$ MRs/m		$\mu/R=0.05$ MRs/m	
	$\delta=0.9$	$\delta=0.8$	$\delta=0.9$	$\delta=0.8$
Context-based – Cell	75.4	65.2	84.7	60.8
Context-based – Ring	96.0	95.8	97.8	94.3

The results depicted in Table II.a show that using the context information per ring rather than per cell allows achieving results very close to the optimum configuration and the ‘Full knowledge’ reference scheme. Table II.a also shows that the energy performance differences between the two variants of the context-based proposal are not very significant under uniform spatial distribution of nodes. However, these differences significantly increase under non-uniform spatial distribution of nodes within the cell. For this scenario, using the context information per ring provides very significant energy benefits when adopting the proposed context-based opportunistic forwarding scheme that again is capable to achieve energy benefits close to that obtained with the optimum configuration and the ‘Full knowledge’ reference scheme. It is important noting that the context-based proposal estimates the time at which an MR will arrive at the identified optimum location using information about the density of nodes. When nodes are non-uniformly distributed per cell, the use of density information per cell can result in incorrect estimations of the time at which an MR will arrived at the identified optimum location, and therefore in incorrect estimations of the time  $t$ . When a MR does not arrive at the identified optimum location within the estimated time, the SN directly communicates with the BS using single-hop cellular communications. The incorrect estimation of the time  $t$  when using context-information per cell under non-uniform distribution of nodes within the cell is actually shown in Table III.b. This table shows that the variant that uses context information at the cell level significantly reduces the hit rate or percentage of connections established using 2-hop opportunistic MCN links with respect to the variant that exploits context information provided per

ring. The lower percentage of established 2-hop opportunistic MCN links results in the higher energy consumption levels depicted in Table II.b under non-uniform distribution of users within the cell.

The results reported in Table II show the average performance of the proposed context-based opportunistic forwarding scheme independently of whether the transmission of data from SN to the BS took place using a 2-hop opportunistic MCN link or single-hop cellular one (the single-hop cellular link is used when no MR is found at the optimal location before  $t$  expires). Table IV reports the energy performance achieved by the proposed context-based scheme when only considering the SN-BS transmissions that took place using a 2-hop opportunistic MCN link. The obtained results show that in this case the context-based proposal achieves very similar energy performance levels to that obtained with the optimum configuration and the ‘Full knowledge’ reference scheme (Table II).

Table IV. Reduction (in percentage) of the total average energy consumption compared to single-hop cellular communications (only 2-hop opportunistic MCN transmissions).

a) Uniform Spatial Distribution of MRs				
Technique	$\mu/R=0.1$ MRs/m		$\mu/R=0.05$ MRs/m	
	$\delta=0.9$	$\delta=0.8$	$\delta=0.9$	$\delta=0.8$
Context-based – Cell	96.62	96.53	96.35	96.47
Context-based – Ring	96.58	96.50	96.35	96.46

b) Non-uniform Spatial Distribution of MRs				
Technique	$\mu/R=0.1$ MRs/m		$\mu/R=0.05$ MRs/m	
	$\delta=0.9$	$\delta=0.8$	$\delta=0.9$	$\delta=0.8$
Context-based – Cell	96.77	96.22	95.80	96.65
Context-based – Ring	95.00	95.63	94.93	95.77

## 6. Conclusions

MCN networks can help address the cellular challenges resulting from the exponential growth of data traffic. To this aim, this study proposes the adoption of opportunistic forwarding schemes particularly suited for delay tolerant services. In particular, the study proposes and evaluates a context-based opportunistic forwarding scheme for MCN networks that can significantly reduce the energy consumption compared to traditional single-hop cellular communications. The proposed scheme exploits context information available from cellular networks to define its operation, and achieve energy performance levels close to that obtained with optimum (but unfeasible) configurations. The proposed scheme achieves its highest performance when the context information is provided per ring rather than per cell. In this case, the context-based proposal can reduce on average the energy consumption of traditional single-hop cellular communications by as much as 96%.



## Acknowledgment

This work is supported in part by the Spanish Ministry of Economy and Competitiveness and FEDER funds (TEC2011-26109), and the Local Government of Valencia with reference ACIF/2010/161 and BEFPI/2012/065. The work is also partially supported by the FP7 ITN CROSSFIRE project.

## References

- [1] 3GPP TR 22.803 V12.1.0. Technical Specification Group Services and System Aspects; Feasibility study for Proximity Services (ProSe). Mar. 2013.
- [2] Y. Yang, H. Hu, J. Xu and G. Mao, "Relay technologies for WiMax and LTE-advanced mobile systems", *IEEE Communications Magazine*, vol. 47, no. 10, pp. 100-105, Oct. 2009.
- [3] J. Gozalvez and B. Coll-Perales, "Experimental Evaluation of Multihop Cellular Networks Using Mobile Relays", *IEEE Communications Magazine*, vol. 51, no. 7, pp. 122-129, Jul. 2013.
- [4] L. Pelusi, A. Passarella and M. Conti, "Opportunistic networking: data forwarding in disconnected mobile ad hoc networks", *IEEE Communications Magazine*, vol. 44, pp. 134-141, Nov. 2006.
- [5] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012–2017. *Cisco White Paper*, Feb. 2013.
- [6] A. Radwan and H.S. Hassanein, "Does Multi-hop Communication Extend the Battery Life of Mobile Terminals?", *Proceedings of the IEEE GLOBECOM*, pp. 1-5, San Francisco, USA, Nov. 27 - Dec. 1, 2006.
- [7] Z. Ruifeng, J.M. Gorce and K. Jaffres-Runser, "Low Bound of Energy-Latency Trade-Off of Opportunistic Routing in Multi-Hop Networks", *Proceedings of IEEE ICC*, pp. 1-6, Dresden, Germany, 14-18 Jun. 2009.
- [8] S. Dimatteo, P. Hui, B. Han and V.O.K Li, "Cellular Traffic Offloading through WiFi Networks", *Proceedings of the IEEE MASS*, pp. 192-201, Valencia, Spain, 17-22 Oct. 2011.
- [9] P. Kolios, V. Friderikos and K. Papadaki, "Future Wireless Mobile Networks", *IEEE Vehicular Technology Magazine*, vol.6, no.1, pp.24-30, Mar. 2011.
- [10] B. Zhao and V. Friderikos, "Optimal stopping for energy efficiency with delay constraints in Cognitive Radio networks", *Proceedings of the IEEE PIMRC*, pp.820-825, Sydney, Australia, 9-12 Sept. 2012.
- [11] WINNER consortium, "D1.1.2 V.1.1. WINNER II channel models", *WINNER European Research project Public Deliverable*, Nov. 2007.
- [12] P. Bertrand, J. Jiang and A. Ekpenyong, "Link Adaptation Control in LTE Uplink", *Proceedings of the IEEE VTC Fall*, pp.1-5, Quebec, Canada, 3-6 Sept. 2012.
- [13] F.D. Calabrese, et al., "Adaptive Transmission Bandwidth Based Packet Scheduling for LTE Uplink" *Proceedings of the IEEE VTC Fall*, pp. 1-5, Calgary, Canada, 21-24 Sept. 2008.
- [14] 3GPP TR 28.814 V7.1.0. Physical Layer Aspects for Evolved UTRA. Sept. 2006.
- [15] 3GPP TS 36.213 V11.4.0. Physical layer procedures for Evolved UTRA. Sept. 2013.
- [16] A. Duda, "Understanding the Performance of 802.11 Networks", *Proceedings of the IEEE PIMRC*, pp.1-6, Cannes, France, 15-18 Sept. 2008.
- [17] B. Coll-Perales, J. Gozalvez and J. Sanchez-Soriano, "Empirical Performance Models for Peer-to-Peer and Two hops Multi-hop Cellular Networks with Mobile Relays", *Proceedings of the ACM PM2HW2N*, Barcelona, Spain, 3-8 Nov. 2013.
- [18] M. Greenberg, "How Much Power Will a Low-Power SDRAM Save you?", White Paper Denali Software, 2009.
- [19] A. Carroll and G. Heiser, "An analysis of power consumption in a smartphone", *Proceedings of the USENIXATC*, pp. 21-25, Boston, USA, 23-25 Jun. 2010.
- [20] B. Karp and H Kung, "Greedy Perimeter Stateless Routing for Wireless Networks", *Proceedings of the ACM/IEEE MobiCom*, pp.243-254, Boston, USA, 6-11 Aug. 2000.
- [21] A. Chaintreau et al., "Impact of Human Mobility on Opportunistic Forwarding Algorithms," *IEEE Transactions on Mobile Computing*, vol.6, no.6, pp. 606-620, Jun. 2007.
- [22] D.C. Montgomery and G.C. Runger, *Applied Statistics and Probability for Engineers*. Wiley, 2011.
- [23] M. Elalem and L. Zhao, "Realistic User Distribution and its Impact on Capacity and Coverage for a WCDMA Mobile Network", *Proceedings of the IEEE SARNOFF*, pp.1-5, New Jersey, USA, Mar. 30-Apr. 1 2009.
- [24] C. Bettstetter, "Topology properties of Ad hoc networks with random waypoint mobility", *ACM SIGMOBILE Mobile Computing and Communications Review*, vol.7, no.3, Jul. 2003.
- [25] I. Stojmenovic and X. Lin, "Power-Aware Localized Routing in Wireless Networks", *IEEE Transaction on Parallel Distributed Systems*, vol.12, no.11, pp. 1122-1133, Nov. 2001.